Development of piezo-actuated wings for flapping wing Micro Air Vehicle

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Flapping wing concept is emerging area in the Micro Air Vehicle (MAV) research. Extensive efforts are being done in this direction to replace gear and motor arrangement. In the present work, a mylar film with Polyvinylidene Fluoride or PVDF as actuator is demonstrated for the flapping in the frequency range of 3-16Hz. Specimens were prepared with different length and width ratios of mylar film. Uniaxially stretched and high quality poled PVDF films have been used for this application. Various parameters have been optimized to obtain maximum deflection of Mylar film by using PVDF as an actuator. The maximum displacement of flapping recorded was 5.78mm at 12Hz resonance frequency. Results have been validated using Ansys via modal & harmonic analysis.

1. INTRODUCTION

The concept of micro-sized Unmanned Aerial Vehicles (UAVs) or Micro Air Vehicles (MAVs) has gained increasing interest over the past few years, with the aim of carrying out surveillance missions [1]. The parameters that are critical to MAV execute/conduct *Intelligence, Surveillance & Reconnaissance (ISR)* missions are size, weight, payload and ability to operate in stealth mode. Lightweight, low-speed MAVs are often more rigid than larger vehicles due to the non linear scaling of the strength of materials. MAVs design presents new challenges to the aerospace engineer because they operate in relatively new flight regimes where classical design methods begin to fail for reasons associated with the physical characteristics of air flow around small surfaces.

An approach in the field of MAV designs is required seeking high levels of maneuverability and aerodynamic efficiency, inspired by the birds, bats and flying insects [2-6]. While birds and bats possess active musculature along the span of the wing [7], insects have textured, flexible and thin wings that passively bend and twist appreciably in flight, leading to instantaneous changes in aerodynamic behavior. Flexible airfoils for MAVs have been used by various authors keeping above features in mind [8, 9].

Several groups across various universities have developed their flapping MAVs with different configurations and actuation principles [10-13]. Irrespective of the scale of the model, the general structure involves a motor which drives gears and linkages to achieve the flapping action. The proposed work envisages the replacement of currently employed motor and gear system, by the use of flexible PVDF for actuating the flapping action. The adaptability of PVDF as a sensor as well as actuator, would greatly aid in active control of the wing aerodynamics. PVDF has been used for the present investigation owing to its transparency, good piezoelectric property, chemical inertness, flexibility, lightness and ability to be flesh mounted or embedded in situ. The novel approach of replacement of gear and motor approach, with PVDF as actuator, would aid the weight reduction and further miniaturization of the design. Our work is aimed to accomplish the state of the art technology in the flapping wing of MAVs with PVDF as actuator.

With the advent of computer technology in the last few decades, new product to be launched in the market is first generated in virtual environment and thereafter, simulated like a real prototype model using finite element technique. This technique helps in generating several virtual models without building a physical prototype and helps in creating a better product by performing more iteration of several design solutions. Finite element technique can now be used to simulate piezoelectric behavior of the existing structure material.

This paper presents flapping of Mylar sheet using PVDF piezoelectric actuators at resonance. Resonant frequencies of Mylar sheet coupled with PVDF films have been obtained through model analysis of general purpose commercially available finite element solver ANSYS. Harmonic analysis has been carried out to evaluate tip deflection at the tip of the sheet by using piezoelectric coefficients at resonant frequencies. Experimental studies have been carried out and compared with numerical results.

2. Specimen design:

Flapping wing concept has been studied by considering wing as a cantilever beam. A cantilever beam here consists of PVDF film fixed on the Mylar film. The main function of PVDF is to actuate the Mylar film. The properties of PVDF films developed at CSIR-NAL [14, 15] and Mylar film have been presented in Table 1 and 2 respectively.

The optimization of the dimensions of PVDF and Mylar film; and location of PVDF actuator on the wing are critical to achieve the desired flapping action of the wings. The thickness of PVDF and Mylar are coupled variables which ought to be optimized to get the required flapping frequency. The specimen design is shown in Figure 1a. The actual specimen is shown in Figure 1b.

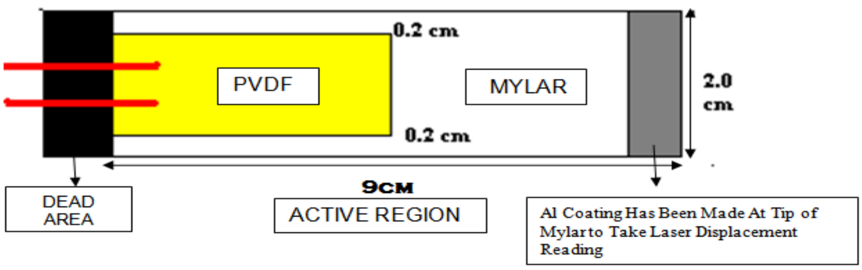


Figure 1a: Design of the specimen

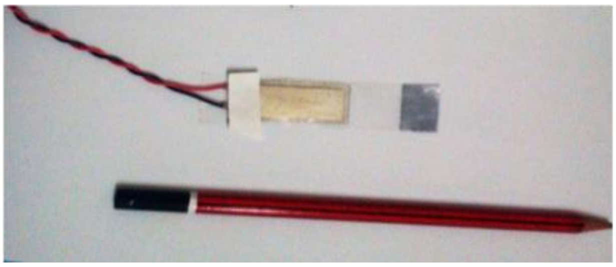


Figure 1b: Actual specimen

Table 1: Properties of PVDF film prepared at NAL

Piezoelectric voltage co-efficient, d_{33}	25 pC/N
Tensile Strength, TS	150 MPa
Tensile Modulus, TM	1.5 GPa
Young's modulus, E	2 GPa
Poisson's ratio, γ	0.29
Density, ρ	1790kg/m^3

The standard dimension of length 40 mm, width 16mm and thickness of 0.205mm of PVDF film were used in all the flapping experiment. Mylar film of various dimensions was taken for this study. The bare side of PVDF was bonded on to the Mylar film using a suitable bonding agent.

Table 2: Properties of Mylar film

Density	1390kg/m^3
Young's modulus	3-5GPa
Poisson's ratio	0.35-0.38

The displacement of Mylar film has been measured using Laser Displacement unit (Micro-Epsilon 1302). The opaque Aluminium coating has been done at the end of the Mylar film as shown in Figure 1 for measuring the displacement.

3. Modeling of the specimen:

The beam structure with various dimensions as listed in the Table 3 for Mylar sheet and constant dimensions of PVDF film as 42.5 X 16 X 0.206 mm is modeled using 3D solid elements, and the PVDF films are modeled by 3D coupled field piezoelectric elements. Both modal analysis and harmonic response analysis are performed to obtain the resonant frequencies and tip deflection at the end of the flapping wing.

Three dimensional solid model of rectangular Mylar sheet with dimensions shown in Figure 1 along with PVDF is generated using general purpose finite element modeling package ANSYS. This model consists of 3-D 20 node solid-186 elements for Mylar sheet. This element exhibits quadratic displacement behavior and having three degree of freedom per node. Piezoelectric behavior of the PVDF material is simulated using three dimensional 20-node solid-226 piezoelectric elements. The element has twenty nodes with up to five degrees of freedom per node. Structural capabilities are elastic only and include large deflection and stress stiffening.

This cantilever beam structure shown is fixed like a cantilever beam at one end and other end of the beam is kept free to vibrate. Loads in the form of voltage is applied at the nodes and appropriate material properties as shown in Table 1 and 2 of Mylar sheet and piezoelectric PVDF material has been input to obtain accurate normal deflection at the end of the flapping wing.

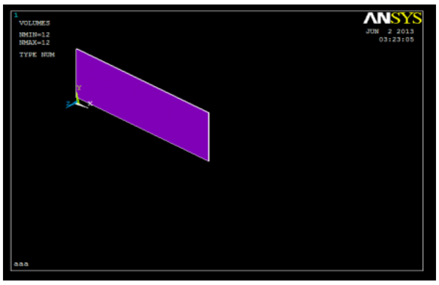


Fig 2a: Modeling of PVDF

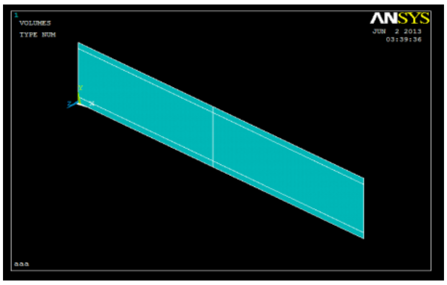


Fig 2b: Modeling of Mylar film

The bonded specimen was modeled as shown in Figure 3 and the effect of voltage on solid element 226 of PVDF film is shown in Figure 4

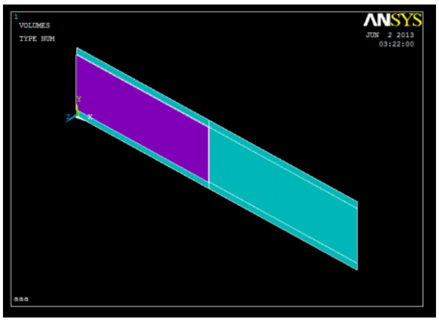


Fig 3: Bonding of Mylar with PVDF

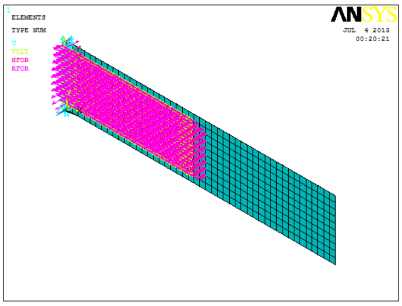


Fig4: Effect of voltage on PVDF film

4. Experimental Setup:

Figure 5 presents the block diagram of the experimental setup for flapping wing displacement measurement.

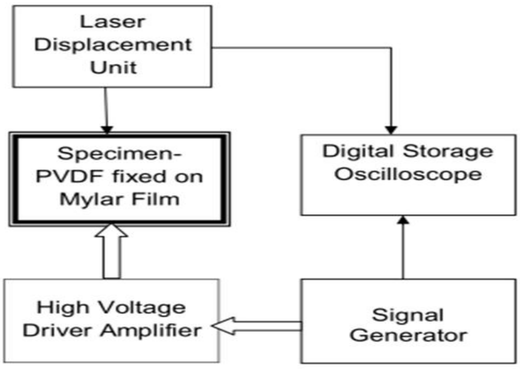
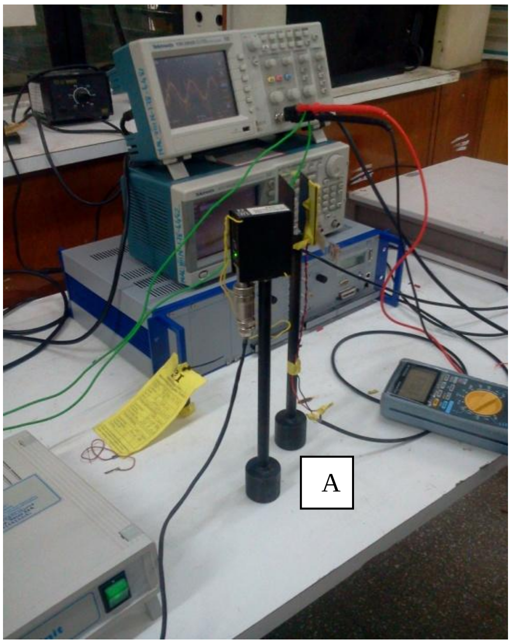


Fig 5: Block diagram of the experimental setup.

The signal generator generates the flapping frequency. A sinusoidal voltage of maximum $3V_{pp}$ from the signal generator was fed to the piezo driver/amplifier (PZD 350A), before being fed to the specimen. The frequency of the driving voltage was adjusted to operate at resonant frequency, in order to obtain maximum displacement which is measured using LASER displacement unit. The experimental setup has been shown in Figure 6.



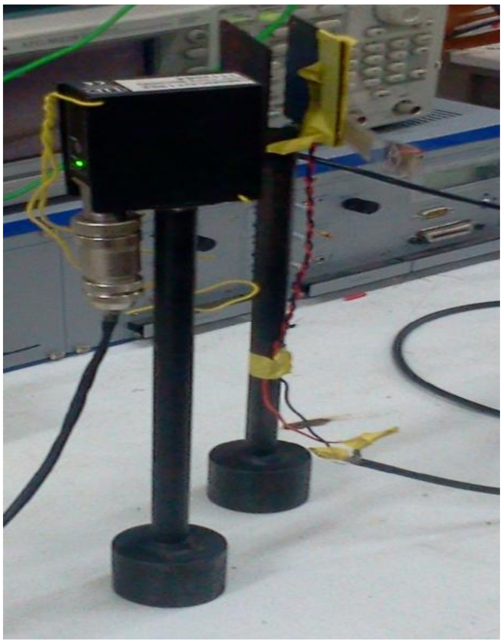


Figure 6a Test setup (b) Magnified view of ‘A’ in Figure 6a

5. Results & Discussions:

Numerical Results:

Natural frequencies of Mylar sheet having 90, 20 and 0.025 mm length, breadth and thickness respectively, bonded with PVDF film have been obtained using modal analysis. Thereafter, harmonic analysis has been carried out at the natural frequencies to obtain deflection at the end of specimen. These studies have been carried out from 3 to 16 Hz frequencies to obtain maximum deflection for flapping wing application. Figure 7 shows four different modes of this flapping wing specimen at 2.72, 13.14, 15.4 and 22.48 Hertz.

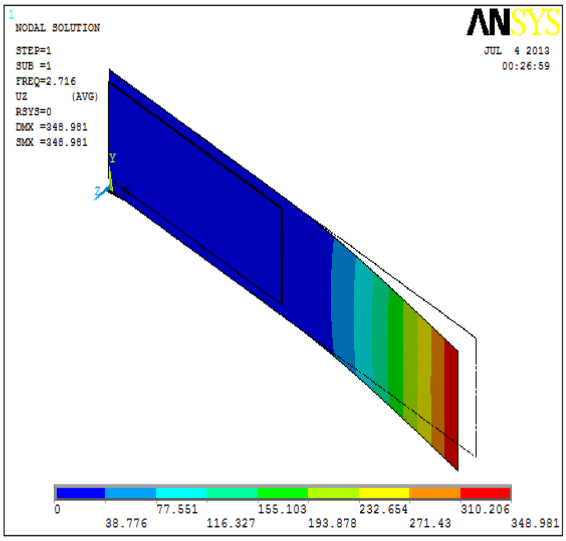


Fig 7a: Mode 1 at 2.72 Hz

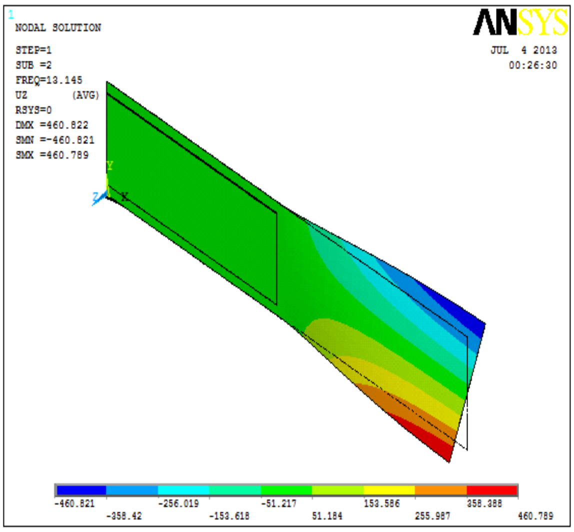
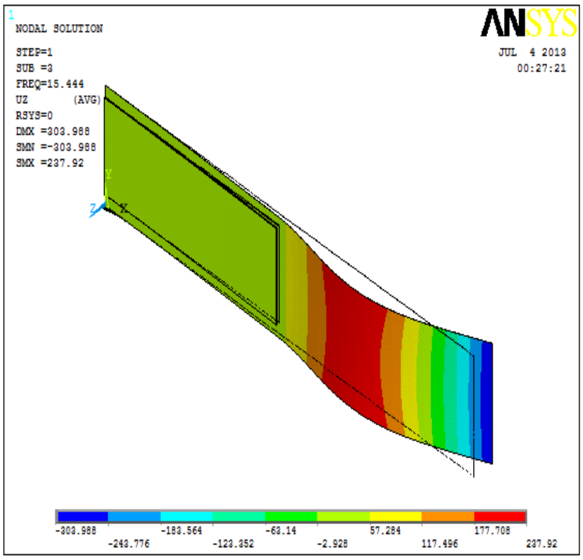


Fig 7b: Mode 2 at 13.14Hz



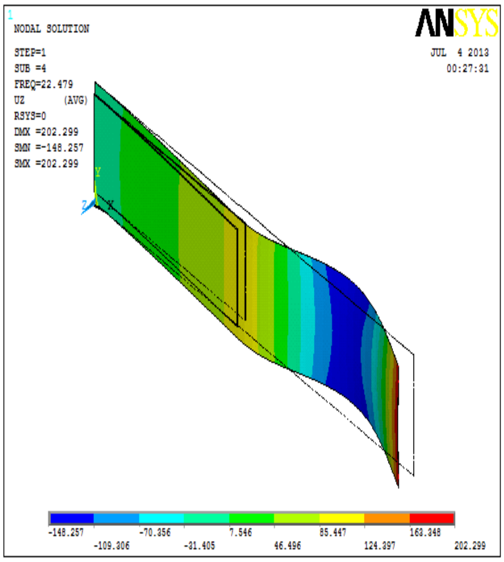
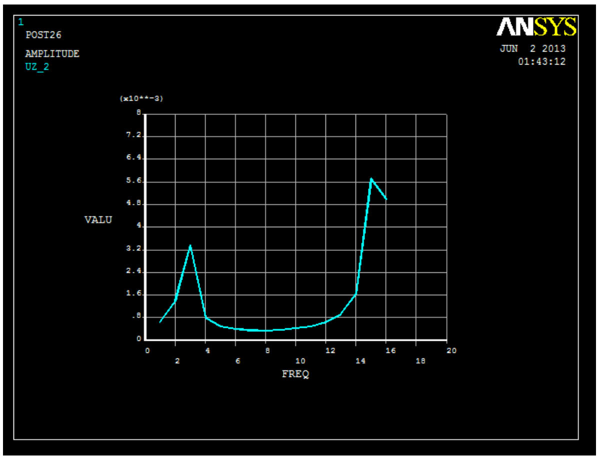


Fig 7c: Mode 3 at 15.44 Hz

Fig 7d: Mode 4 at 22.48Hz

Finite element analysis shows that at natural frequency of 15Hz, maximum deflection at the end of the specimen is 5.916 mm as shown in Figure 8a and b.



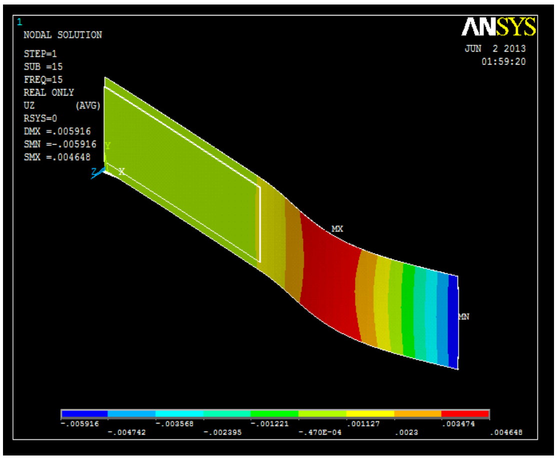


Figure 8a: Frequency Vs. Displacement

Figure 8b: Mode shape at 15Hz

Experimental Results:

A Number of experiments were conducted by changing the length, breadth and thickness of Mylar film while keeping the dimensions of PVDF as 42.5 X 16 X 0.206 mm. The resonance frequency and displacement corresponding to different dimensions of Mylar has been presented in Table 3. The maximum displacement of 5.916mm was found for Mylar dimension of 90 X 20 mm for 0.025mm thickness. The same experiment was conducted by doubling the thickness of the Mylar film and it was found that displacement has become approximately half while resonance frequency has reduced from 12 to 9Hz.

Table 3: Comparison of Experimental and Analytical results:

Sl. No	Length(L), width(w) and thickness(t) of Mylar(mm)			Experiment Results		Ansys Results	
	L	W	T	Resonance Frequency (Hz)	Displacement (mm)	Resonance Frequency (Hz)	Displacement (mm)
1	90	16	0.025	14	0.783	16	0.815
2	90	20	0.025	12	5.781	15	5.916
3	90	24	0.025	10	3.001	8	3.213
4	90	28	0.025	07	3.272	8	3.552
5	60	20	0.025	16	1.303	16	1.561
6	90	30	0.025	04	3.653	04	3.783
7	90	20	0.050	09	2.652	09	2.563

From the experimental results it was found that PVDF can actuate Mylar film and can be used for MAV’s flapping wing applications.

Conclusion:

Experimental and numerical studies have been carried out to predict normal tip deflection at the free end of flapping wing. Different length and width of Mylar film bonded with PVDF film has been taken for the present study. This has been excited by piezoelectric flexible actuators at natural frequencies. The modal and harmonic analysis has been carried out using ANSYS finite element solver. Analysis shows excellent comparison in between numerical and experimental results at all the frequencies considered in this paper. Present investigation shows that maximum deflection of 5.781 mm is obtained at 12Hz resonant frequency.

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References:

1. Raibert, M., Blankespoor, K., Nelson, G., Playter, R., and the BigDog Team, 2008. “Bigdog, the rough-terrain quadruped robot”. Proceedings of the 17th World Congress, The International Federation of Automatic Control.

2. Fearing R S, Chiang K H, Dickinson M H, Pick D L, Sitti M and Yan J A 2000 Wing transmission for a micromechanical flying insect IEEE Proc. ICRA'00 Int. Conf. on Robotics and Automation 2000 vol 2 ed K H Chiang pp 1509–16

3. Wood R J, Design, fabrication, and analysis of a 3DOF, 3 cm flapping-wing MAV IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (San Diego, CA) 2007.

4. Tanaka H, Hoshino K, Matsumoto K and Shimoyama I 2005 Flight dynamics of a butterfly-type ornithopter IEEE/RSJ Int. Conf. on Intelligent Robots and Systems pp 2706–11.

5. Pornsin-Sirirak T, Tai Y, C Ho and KeennonM2001 Microbat: a palm-sized electrically powered ornithopter Proc. Of NASA/JPL Workshop on Biomorphic Robotics pp 14–17.

6. Madangopal R, Student G, Khan Z and Agrawal S 2005 Biologically inspired design of small flapping wing air vehicles using four-bar mechanisms and quasi-steady aerodynamics J. Mech. Des. 127 809.

7. Dudley R, The Biomechanics of Insect Flight: Form, Function, Evolution (Princeton, NJ: Princeton University Press) 2000.

8. Shyy W, Ifju P G and Vileru D 2005 Membraned wing-based micro air vehicles Appl. Mech. Rev. 58 283–302.

9. Zhao L, Huang Q, Deng X and Sane S 2009 The effect of chord-wise flexibility on the aerodynamic force generation of flapping wings: experimental studies IEEE Proc. ICRA'09 Int. Conf. on Robotics and Automation, Kobe, Japan, 12–17 May.

10. Website: http://www.artificialmuscle.com/.

11. Website: http://fourier.vuse.vanderbilt.edu/cim/projects/crawler.htm.

12. M. Sitti, PZT actuated four-bar mechanism with two flexible links for micromechanical flying insect thorax, in: Proceedings of the IEEE Robotics and Automation Conference, Korea, 2001, pp. 3893–3900.

13. Website: http://www.gtri.gatech.edu/atas/teams/proj entomopter.html.

14. **Anjana Jain**, Jayanth Kumar S, Srikanth S, V.T. Rathod, D. Roy Mahapatra, Sensitivity of PVDF films to mechanical vibration modes and impact after optimizing stretching conditions, *J. Polymer Engg. And Science*, 53 (2013) 707.

15. V. T. Rathod, D. Roy. Mahapatra, **Anjana Jain**, A. Gayathri, "Characterization of a Large Area PVDF Thin Film for Electro-Mechanical and Ultrasonic Sensing Applications" *Sensors and Actuators A*, **163** (2010),

77 Massachusetts Ave.,33-311

Cambridge, MA 02139

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16. Dae-Kwan Kim, Hong-Il Kim, Jae-Hung Han and Ki-Jung Kwon, Experimental Investigation on the Aerodynamic Characteristics of a Bio-mimetic Flapping Wing with Macro-fiber Composites, Journal of Intelligent Material Systems and Structures 2008 19: 423